THE AXIDENTAL UNIVERSE

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"The universality of fundamental physics lies behind the account given in the forthcoming chapters. […] although the specific details of physical systems can only be determined from complicated analyses, the broad structural features are largely determined from a few elementary considerations."

[P.C.W. Davies, *The Accidental Universe* (1982)]

$$\rho_{\rm Inf} \sim M_{\rm GUT}^4$$

$$N_{\rm e} \sim \frac{1}{4}\log\left(\frac{M_{\rm GUT}^4}{\rho_{\rm today}}\right)$$

$$\frac{\delta T_{\rm CMB}}{T_{\rm CMB}} \sim \frac{M_{\rm GUT}^2}{M_{Pl}^2}$$

$$\rho_{\rm matter} \sim 0.1 \times \rho_{\rm today}$$

$$\rho_{\rm today} \sim M_{Pl}^4 e^{-2\frac{M_{Pl}}{M_{\rm GUT}}}$$

"Quantum Gravity"

IIB String Theory: $\mathcal{O}(500)$ cycles say charge conservation allows on average 10 flux units per cycle. Gives $10^{\mathcal{O}(500)}$ 4D theories.

$$M_{\rm GUT} \sim 10^{-2} M_{Pl}$$

4D theories scan in unknown way. Typically $\mathcal{O}(500)$ axions θ^i:

$$\mathcal{L}_{\rm axion} \sim -\frac{1}{4}F^2 - \frac{1}{2}K_{ij}\partial\theta^i\partial\theta^j - V(\theta^i) - \frac{f_\theta}{M_{Pl}}\theta F\tilde{F}$$

Emergent universality: complex multi-axion theory yields physics independent of microscopic details (parameters)

Motivation

$$\mathcal{L}_{\text{axion}} \sim -\frac{1}{4}F^2 - \frac{1}{2}K_{ij}\partial\theta^i\partial\theta^j - V(\theta^i) - \frac{f_\theta}{M_{Pl}}\theta F\tilde{F}$$

$$V(\theta^j) = V_0 + \sum_{I=1}^{P}\Lambda_I^4\left[1-\cos\left(\mathcal{Q}_j^I\theta^j+\delta^I\right)\right]+\ldots$$

$$M_{\text{GUT}} \approx 10^{-2}M_{Pl} \approx 2\times 10^{16}\text{GeV}$$

$$P \gtrsim N \sim 500$$

$$Q_j^I \in \{-1,0,1\}$$

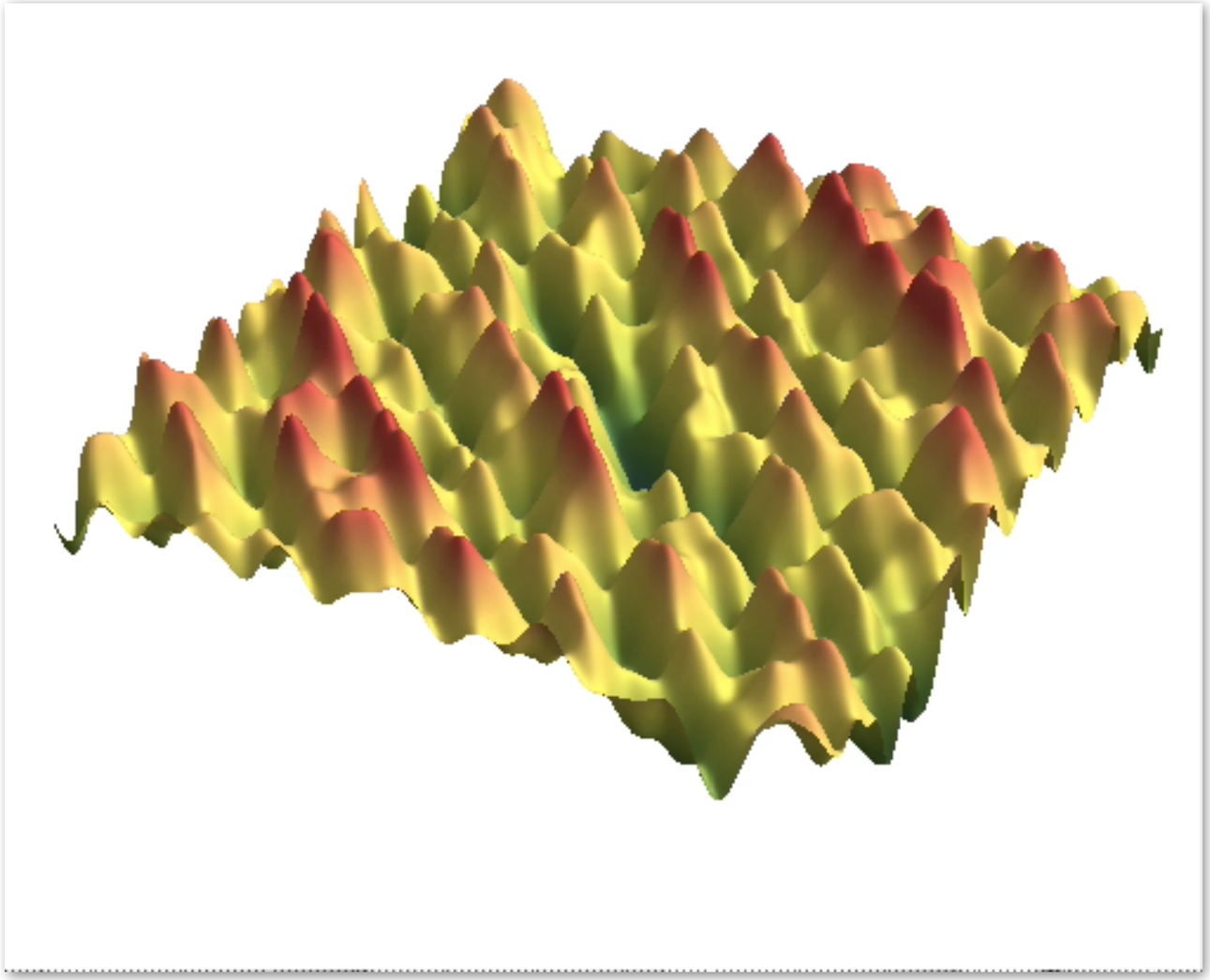
$$\text{Max Eigenvalue}\,(K) \sim M_{\text{GUT}}^2$$

$$\Lambda^{1\ldots P-1} \sim M_{\text{GUT}}\,,\quad \Lambda^P \sim e^{-0.7\frac{M_{Pl}}{M_{\text{GUT}}}}M_{Pl}$$

$$V_0 \sim M_{\text{GUT}}$$

Systematics of Aligned Axions

$$V_{\rm axion} = \sum_{I=1}^{P} \Lambda_I^4 \left[1 - \cos\left(\mathcal{Q}_j^I \theta^j + \delta^I\right)\right] + \dots$$



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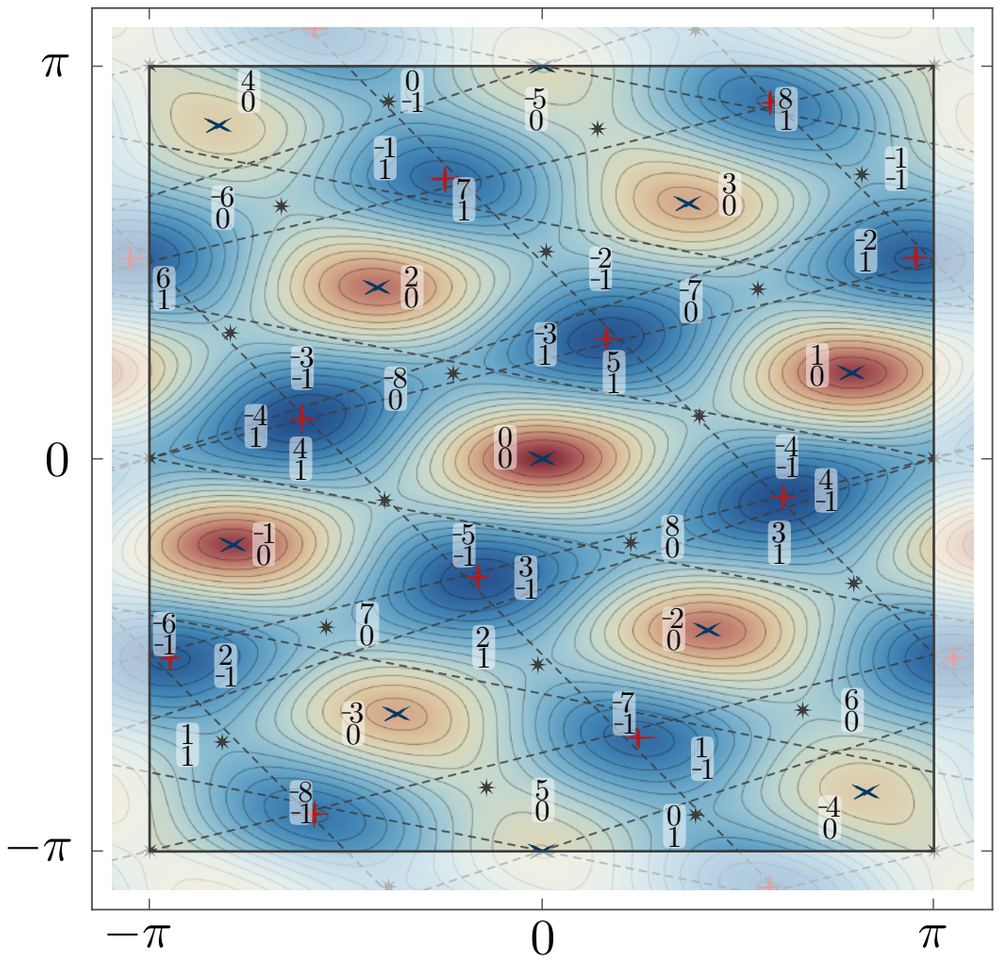


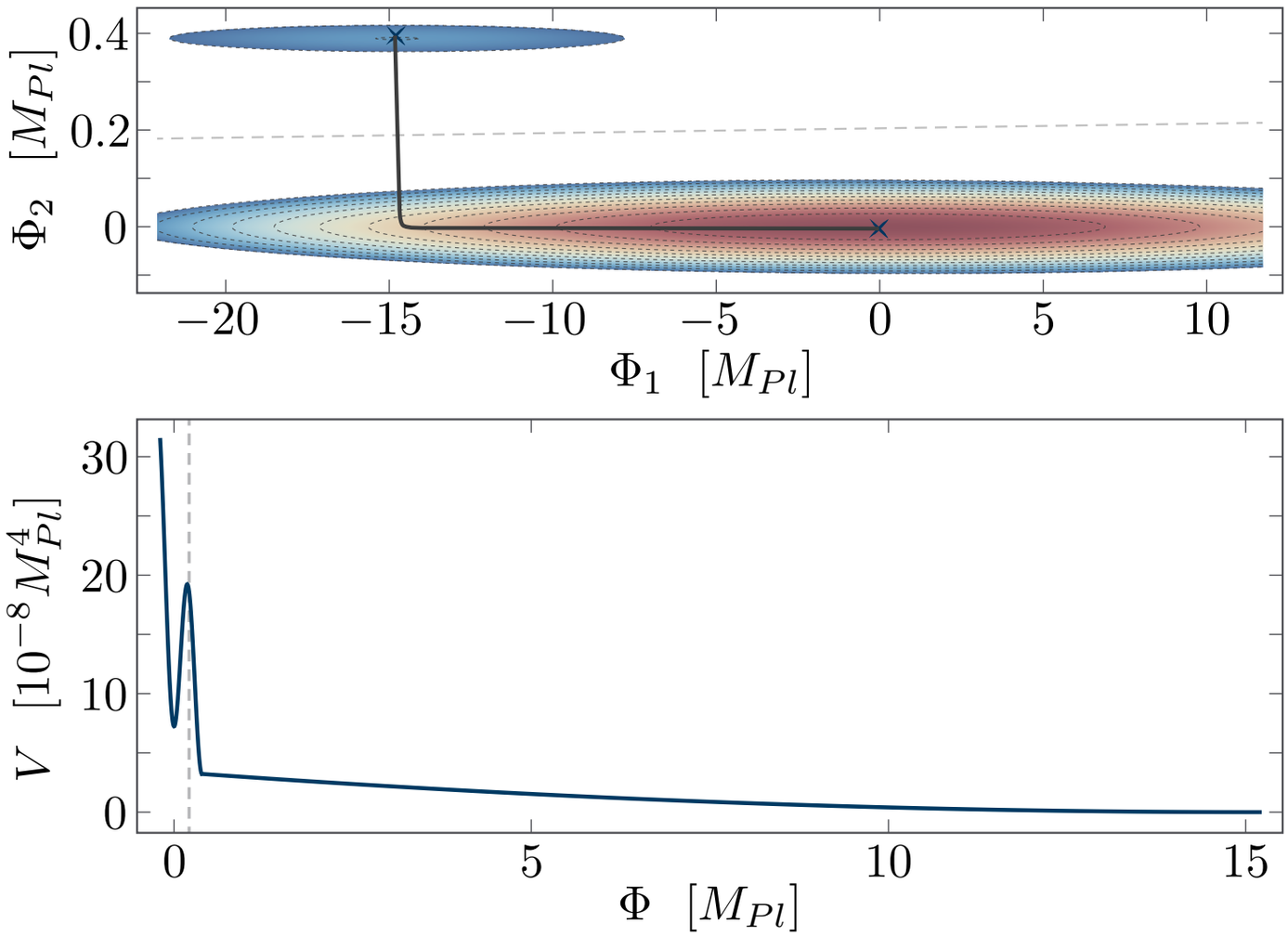
Find vacua analytically.
Number of vacua:

$$\mathcal{N}_{\rm vacua} \sim \langle \mathcal{Q}_j^I \rangle^{P-1} \sqrt{P P!}$$
$$\sim 10^{500}$$

Mathematica Package:
cosmo.nyu.edu/kleban/AxionSystematics.nb

Start in any vacuum.

Vacuum decay via thin-wall CDL or FGG tunneling; no Hawking-Moss $\Gamma_{\rm decay} \ll e^{-10^3} M_{Pl}^4$



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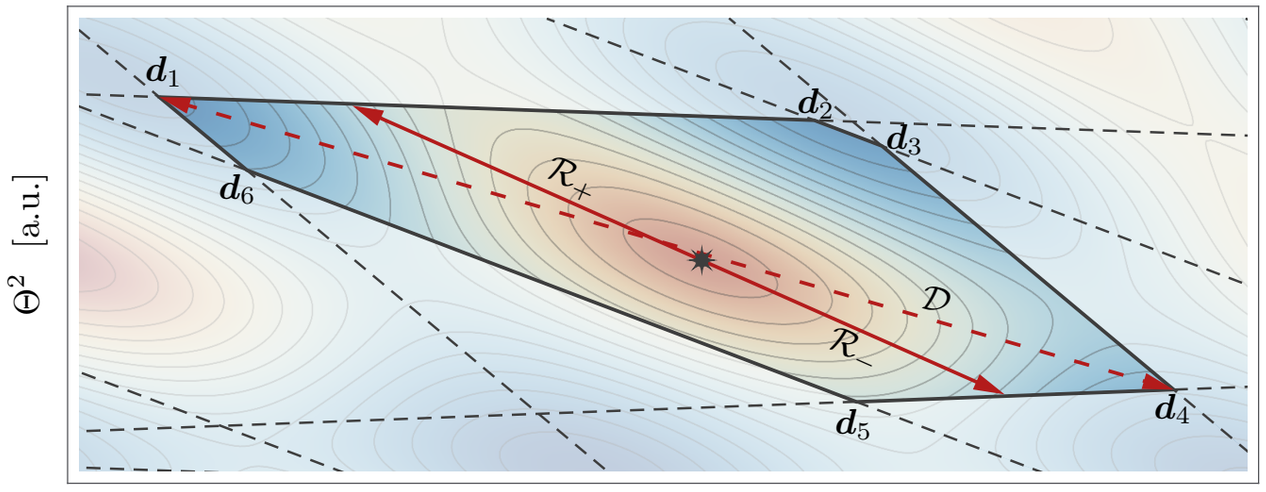


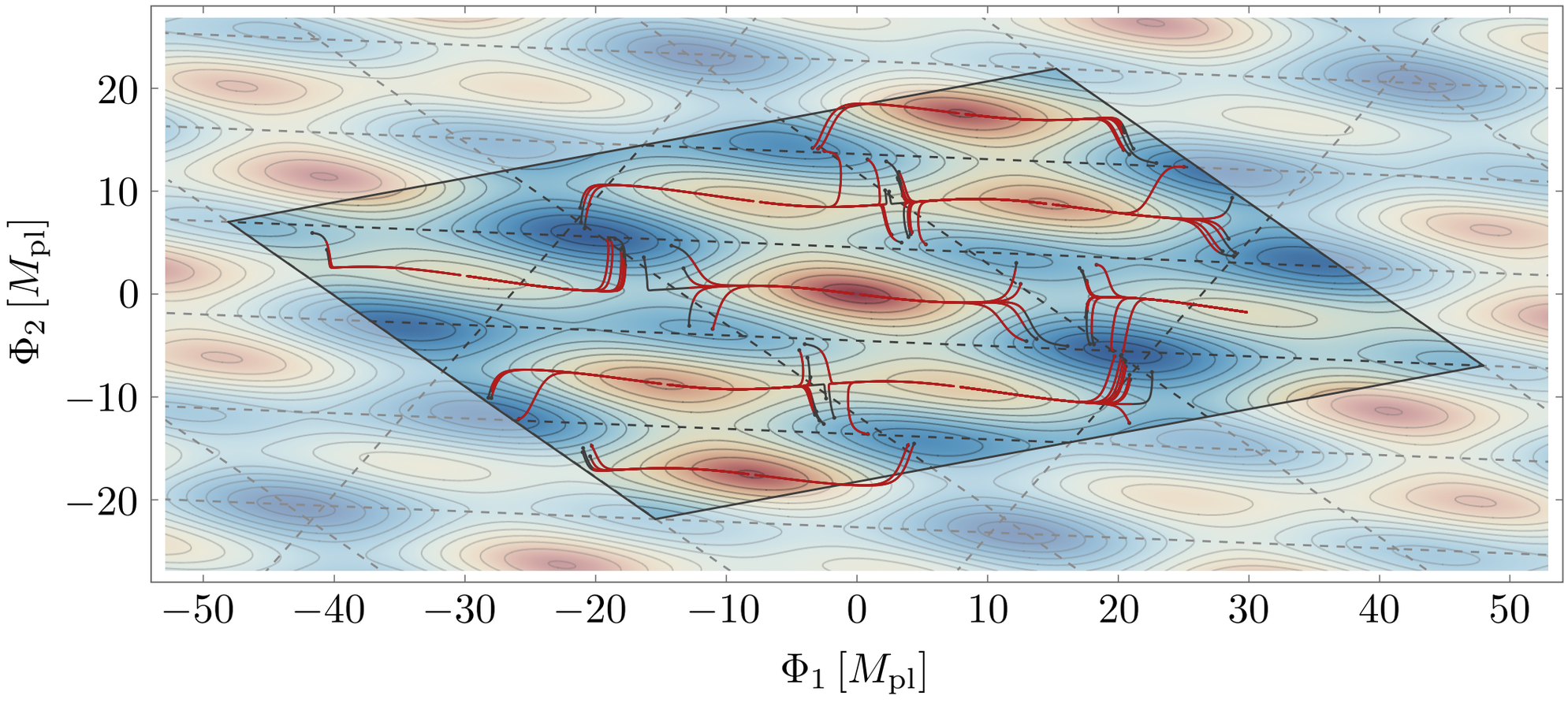
Axions align: $\mathcal{D} \approx 2\pi\sqrt{P}\sqrt{N}\sqrt{N} f_{\max} \sim \mathcal{O}(10) M_{Pl}$

Kinetic Alignment

KNP Alignment

Eigenvalue Repulsion

Simple example: Scan for all inflationary trajectories



$$N = 2,\ P = 3,\ \mathcal{R} \approx 15 M_{\rm pl}$$

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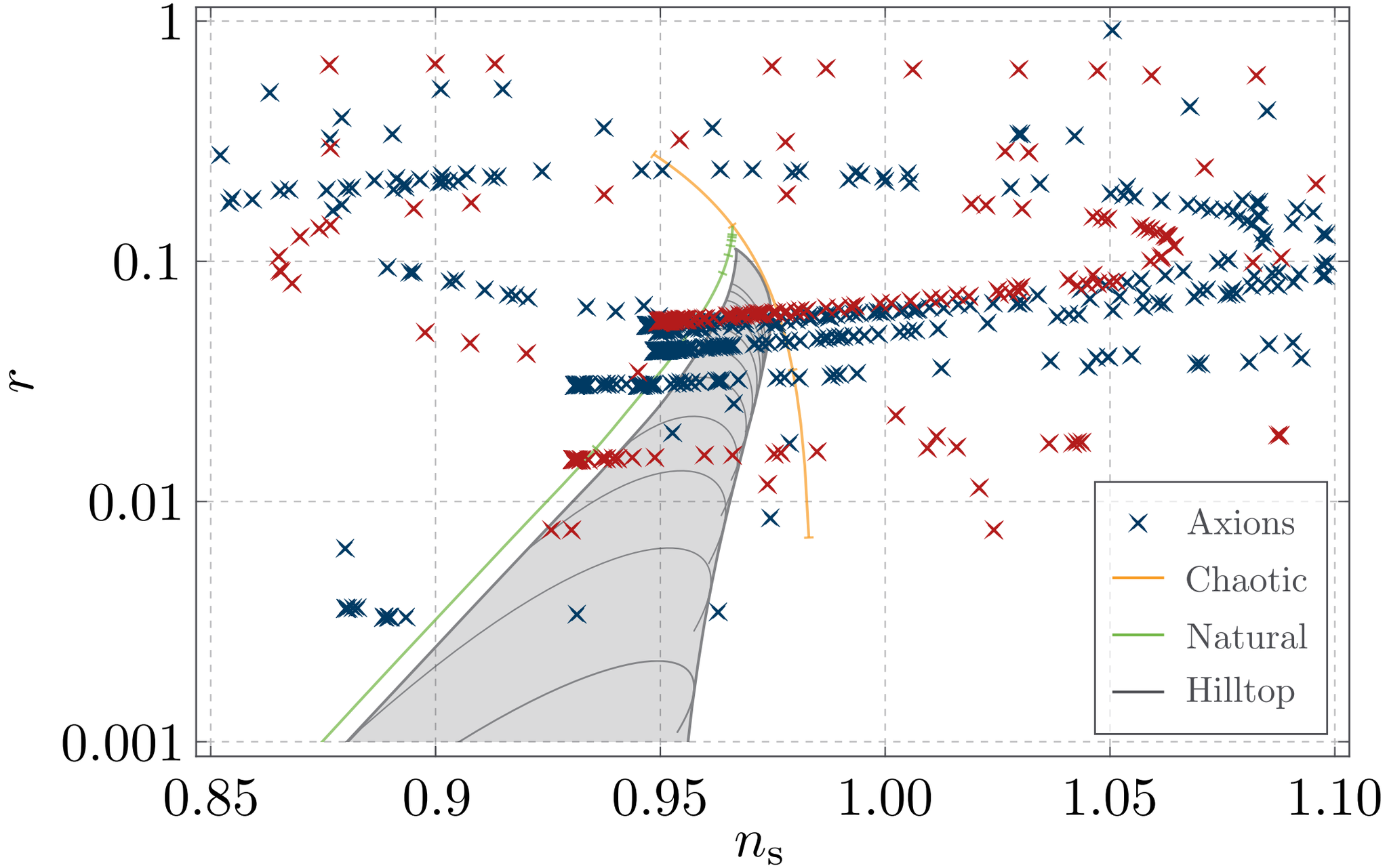

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Multi-Axion Cosmology

Assume small coupling between inflaton and gauge field

$$\frac{0.1}{8\pi f_{\mathrm{inf}F}}\Theta_{\mathrm{inf}}F\tilde{F}$$

Total-derivative in vacuum and consistent with $\Theta \to \Theta + \mathrm{const.}$

At end of slow roll $\epsilon \approx 1$: tachyonic gauge field production.
Lower bound on reheating temperture: perturbative decay.

$$10^{-6} M_{Pl} \lesssim T_{\mathrm{reh}} \lesssim 10^{-2} M_{Pl}$$

Multi-Axion Cosmology

Energy density during radiation domination:

$$\rho_{\rm rad} \sim \frac{T_{\rm reh}^4}{3M_{Pl}^2}\frac{a_{\rm reh}^4}{a^4}$$

Massless axion $\theta_{\rm light} \to \theta_{\rm light} + c$ would be global symmetry.

Smallest possible axion mass set by gravitational instanton:

$$m_{\rm light} \sim \frac{M_{Pl}^2}{f_{\rm light}} e^{-1.4\times M_{Pl}/f_{\rm light}} \sim 10^{-21}{\rm eV}\,, \;\; f_{\rm light} \approx M_{\rm GUT}$$

After $H \lesssim H(a_{\rm osc}) \approx m_{\rm light}$ light axion acts as dark matter:

$$\rho_{\rm DM} \sim m_{\rm light}^2 f_{\rm light}^2 \frac{a_{\rm osc}^3}{a^3}$$

Multi-Axion Cosmology

Matter - radiation equality:

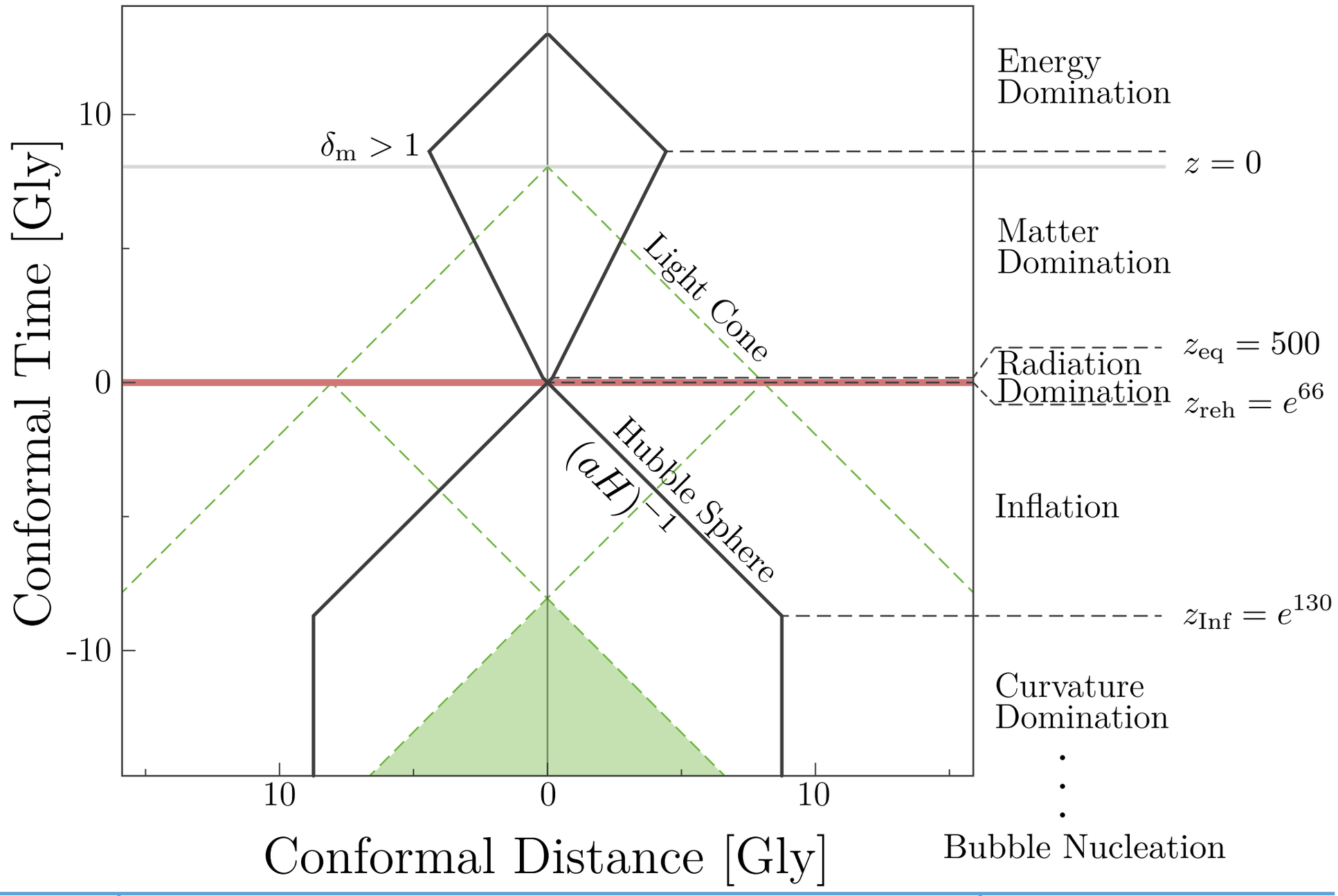
$$\rho_{\rm rad}(a_{\rm eq}) = \rho_{\rm DM}(a_{\rm eq}) \approx 10^{-112} M_{Pl}^4$$

Dark matter perturbations $\delta_{\rm DM} = \delta\rho_{\rm DM}/\rho_{\rm DM}$:
- grow during radiation and matter domination
- suppressed during energy or curvature domination

Time of structure formation $\delta_{\rm DM}(a_{\delta_m=1}) \equiv 1$:

$$\rho_{\rm DM}(a_{\delta_m=1}) \sim 10^{-10} M_{Pl}^4 e^{-2.2\frac{M_{Pl}}{M_{\rm GUT}}} \sim 10^{-121} M_{Pl}^4$$

Typical Cosmology with $\langle \delta_{\rm m} \rangle > 1$



Based on:

TB,
"Axionic Band Structure of the Cosmological Constant"

TB, K. Eckerle, O. Janssen and M. Kleban,
"*Axions of Evil*," 1703.00453
"*Systematics of Aligned Axions*," 1709.01080
"The Axidental Universe"
"*The Cosmology of Multi-Axion Theories*"